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SHOCK TUBE TECHNIQUES AND INSTRUMENTATION

by

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ABSTRACT

A survey of shock tube techniques and instrumentation is presented. Ideal shock tube theory is outlined as are various phenomena which influence actual performance. Shock tubes designed for specific purposes are described. Shock tube instrumentation is discussed in terms of the variable to be measured.

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ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

1. INTRODUCTION

The advent of supersonic flight has created a need for better understanding of shock waves and of the properties of gases processed by shock waves. The shock tube, a laboratory instrument used to generate shock waves under controlled conditions, is a natural tool for experimental investigations of shock-associated phenomena.

The operating regimes of various types of shock tubes (ref 1,2), represented by the areas under the hatch marked lines in figure 1, encompass many interesting re-entry trajectories (ref 3,4). The properties of air in these regimes are typified by the areas above the lines showing complete oxygen and nitrogen dissociation (ref 5). Shock tube studies of the chemical kinetics of these and of other high temperature reactions have been made as have studies of such diverse phenomena as the transport and radiative properties of ionized gases and of the properties of low density hypersonic flow. The purpose of this report is to outline the capabilities and limitations of the shock tube by giving the theory, techniques, and instrumentation involved in its use. Books, monographs, and review articles dealing with shock tubes are listed (ref 6 through 18).

2. GENERAL DISCUSSION

The shock tube most widely used in studies of re-entry phenomena is the pressure-driven, or conventional, shock tube. This is basically a closed tube divided by a diaphragm into two sections of substantially different pressures. Most tubes are brass or steel although glass and wooden tubes have been used. The diaphragms are made of cellophane, copper, aluminum, or steel depending upon the strength of the shock wave required. The diaphragm is ruptured either by increasing the pressure difference between the sections or by puncturing with a mechanical device. The gas from the high pressure (driver) section expands into the low pressure (driven) section of the tube, which contains the test gas. A shock wave propagates into and compresses the test gas. The shock wave typically has a thickness of a few mean free paths and, in an ideal case, the compressed gas reaches its equilibrium values of pressure, density, and temperature in this distance. In reality, the shock wave is followed by an extended region wherein vibrational relaxation, dissociation, ionization, and other effects occur.

A qualitative picture of the events occurring in an idealized case may be obtained from figure 2. The shock travels to the right at a velocity greater than the sonic velocity of the undisturbed test gas, compressing, heating, and accelerating the test gas. Upon reaching the end of the tube the incident shock wave reflects and travels back toward the left, the gas particles behind the reflected shock having zero velocity. The division between the driver and driven gases, which is known as the contact surface or cold front,

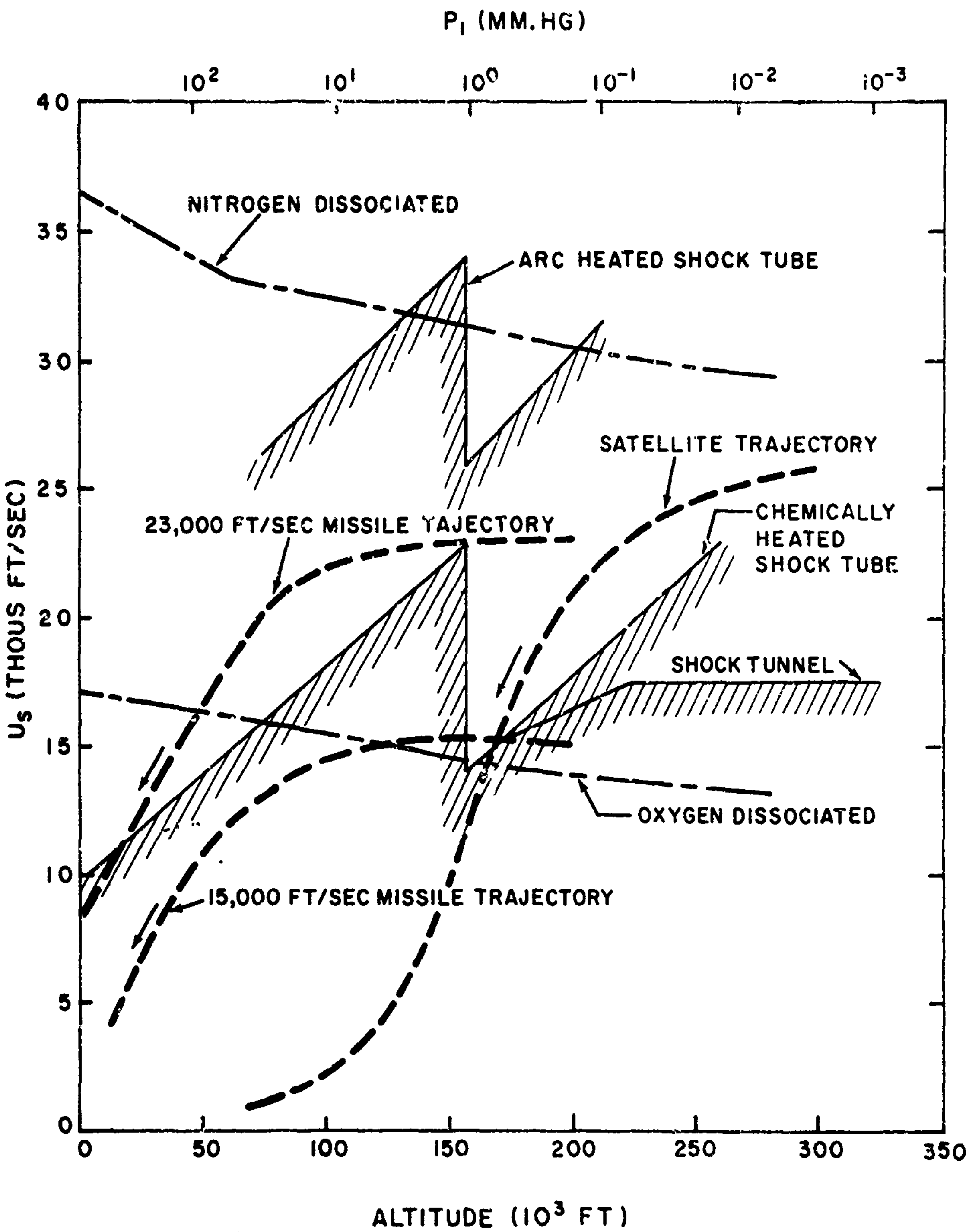

Figure 1. Shock tube and some chemical kinetic regimes together with some missile and satellite trajectories.

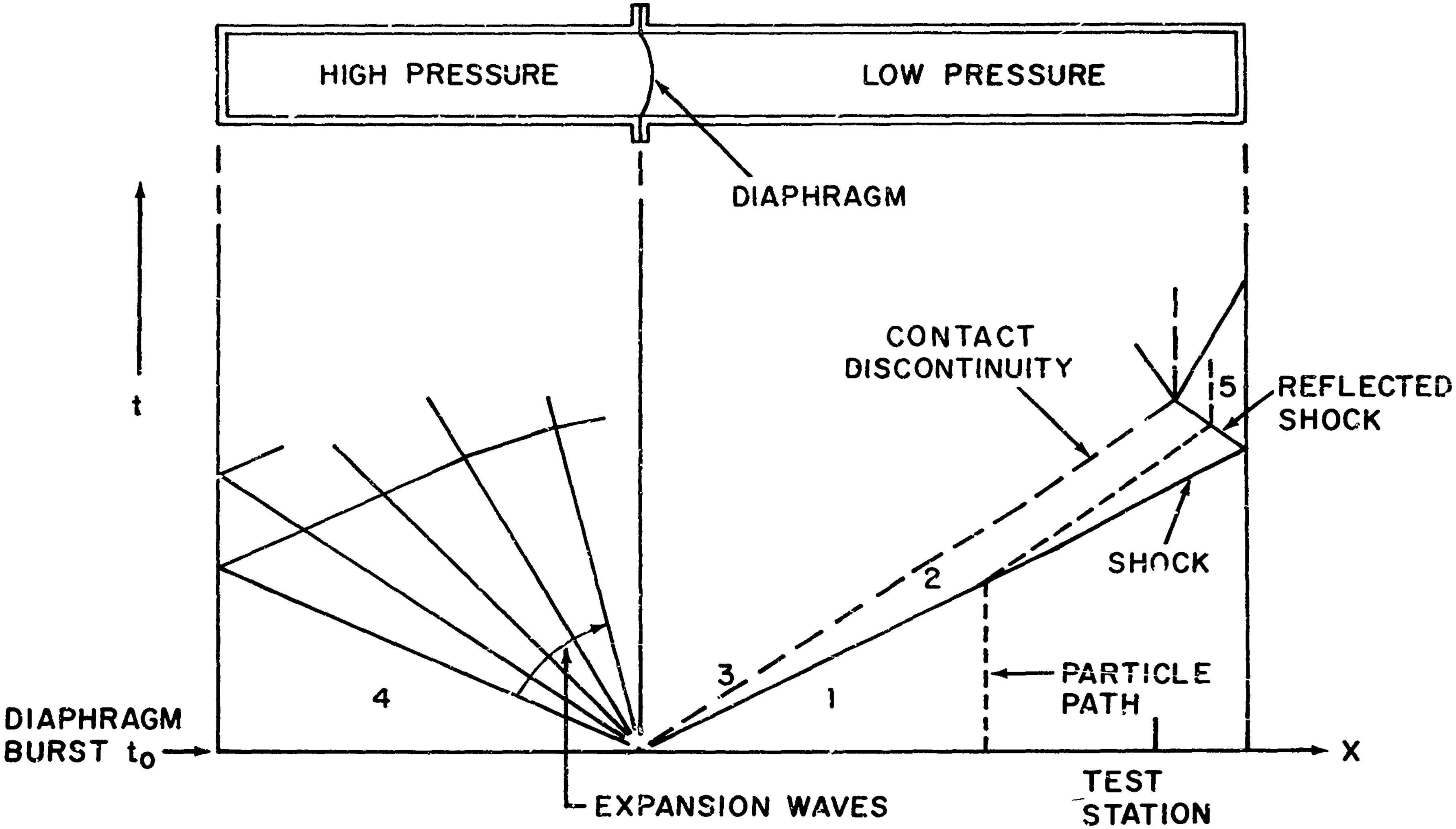

Figure 2. Schematic diagram showing shock-tube wave phenomena.

also proceeds from the diaphragm to the right in the figure. A series of expansion waves, called the expansion fan, starts at the diaphragm and propagates from right to left, reflects from the end wall of the high pressure section, and then travels to the right. If the high pressure section is too short, these reflected expansion waves overtake the contact surface and shock wave, changing the properties of the gas behind the shock wave.

Explosives (ref 19) and a sudden discharge of electricl energy (ref 20) are also used to generate shock waves in tubes. The waves thus formed are blast waves, i.e., shocks followed closely by expansions. The gas temperatures associated with blast waves can be greater than 15,000°K. High temperatures have also been generated in gases driven by pistons (ref 21). Despite the growing usefulness of these techniques, they are seldom utilized in re-entry studies. The discussion in this chapter will be restricted to conventional pressure-driven shock tubes.

3. IDEAL SHOCK TUBE THEORY

The analysis of the ideal behavior of a shock tube assumes (a) initial constituents of the gas do not change, (b) flow processes are adiabatic, (c) opening of the diaphragm is instantaneous and complete, and (d) no reflected waves from the expansion fan overtake the contact surface.

The equations expressing the conservation of mass, momentum, and energy across a normal shock front are

$$\rho_1 v_1 = \rho_2 v_2 \tag{1}$$

$$\rho_1 v_1^2 + P_1 = \rho_2 v_2^2 + P_2 \tag{2}$$

$$h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2} \tag{3}$$

where the coordinate system is referred to the moving shock wave. The quantities P, ρ, v, and h are the pressure, density, velocity, and enthalpy of the gas. Subscripts refer to conditions shown in figure 2; 4 and 1 being the initial driver and driven gas, 2 and 5 being the gas behind the incident and reflected shock wave and 3 being the gas behind the contact surface. To transform these equations to the chock tube coordinate system, we note that

$$v_1 = u_s \tag{4}$$

$$v_2 = u_s - u_2 \tag{5}$$

where u_s is the velocity of the shock wave and u_2 is the velocity of the gas particles behind the shock wave, both velocities measured relative to shock tube coordinates. In this ideal case, the thermodynamic properties of the gas behind the shock are expressed as functions of the shock velocity since this is a readily measured quantity.

From these equations and the equation of state for a perfect gas, one obtains the following relations across the shock wave:

$$P_2/P_1 = (\gamma_1 + 1)^{-1} [2\gamma M_s^2 - \gamma_1 + 1] \tag{6}$$

$$T_2/T_1 = a_2^2/a_1^2 = 2[\gamma_1 + 1)M_2]^{-2} (2\gamma_1 M_s^2 - \gamma_1 + 1)[(\gamma_1 - 1)M_s^2 + 2] \tag{7}$$

$$\rho_2/\rho_1 = [(\gamma_1 - 1)M_s^2 + 2]^{-1} (\gamma_1 + 1)M_s^2 \tag{8}$$

$$u_2/a_1 = 2(M_s^2 - 1)[(\gamma_1 + 1)M_s]^{-1} \tag{9}$$

where M_s is the Mach number of the incident shock wave referred to the sound speed, a_1, γ_1 is the ratio of specific heat at constant pressure to specific heat at constant volume, and T is the gas temperature.

At the contact surface, we have the continuity conditions

$$u_3 = u_2 \tag{10}$$

$$P_3 = P_2 \tag{11}$$

Since the flow across the expansion fan is isentropic, we can obtain the following expression for the pressure ratio across the diaphragm in a tube where the driver and driven sections are of constant area:

$$P_4/P_1 = (2\gamma_1 M_s^2 + 1 - \gamma_1)(\gamma_1 + 1)^{-1} \left[1 - \frac{a_1}{a_4} \left(\frac{\gamma_4 - 1}{\gamma_1 + 1}\right)\left(M_s - \frac{1}{M_s}\right)\right]^{-\frac{2\gamma_4}{\gamma_4 - 1}} \tag{12}$$

As might be expected, this expression indicates that large Mach numbers can be generated by large pressure ratios. The strength of the material of the high pressure section and the opening properties of the diaphragm limit the high pressures that can be utilized. The

low pressure limit may be determined by the state of the art of vacuum technology or by the strength of the material of the downstream tube and associated test stations. Figure 3 shows the results of using equation 12 for a monatomic driver gas and a diatomic driven gas. The ratio of the acoustic velocities of these gases is the parameter used in the figure. Curves for other combinations of γ_1 and γ_4 are given in reference 22. An approximation, useful when $M_s > 3$, may be found in reference 23.

The limiting Mach number for infinite pressure ratios across the diaphragm may be obtained by letting the quantity in the square brackets of equation 12 go to zero and expanding the result:

$$M_{s\infty} = \frac{a_4}{a_1}\ \frac{\gamma_1 + 1}{\gamma_4 - 1}\left(\frac{1}{2} + \frac{1}{2}\sqrt{1 + \left[2\,\frac{a_1}{a_4}\left(\frac{\gamma_4 - 1}{\gamma_1 + 1}\right)\right]^2}\right) \tag{13}$$

Examination of equation 13 indicates that high Mach numbers are obtained when a_4 is made large compared with a_1 (compare with fig. 3) and $(\gamma_4-1)/\gamma_1+1)$ is minimized. For air as the driven gas, and for air, helium, and hydrogen as driver gases, we obtain maximum Mach numbers of approximately 6, 10, and 24, respectively, if all gases are initially at room temperature.

From the conservation equations 1, 2, and 3 written for a reflected shock, together with the condition behind the reflected shock,

$$u_5 = 0 \tag{14}$$

we obtain

$$\frac{u_{rs}}{a_2} = \frac{2\gamma_1 M_s^2 - (\gamma_1 - 1)}{2 + (\gamma_1 - 1)M_s^2} \tag{15}$$

where u_{rs} is the velocity of the reflected shock wave and a_2 is the acoustic velocity in the gas heated by the incident shock wave.

Equations of the form 6, 7, and 8 are also applicable across the reflected shock with the proper change of subscript; i.e., change 1 to 2, 2 to 5 and s to rs. The thermodynamic properties behind the reflected shock may now be expressed in terms of the incident shock waves Mach number:

$$P_5/P_1 = [2\gamma_1 M_s^2 - (\gamma_1 - 1)][3(\gamma_1 - 1)M_s^2 - 2(\gamma_1 - 1)][\gamma_1 + 1)\{(\gamma_1 - 1)M_s^2 + 2\}]^{-1} \tag{16}$$

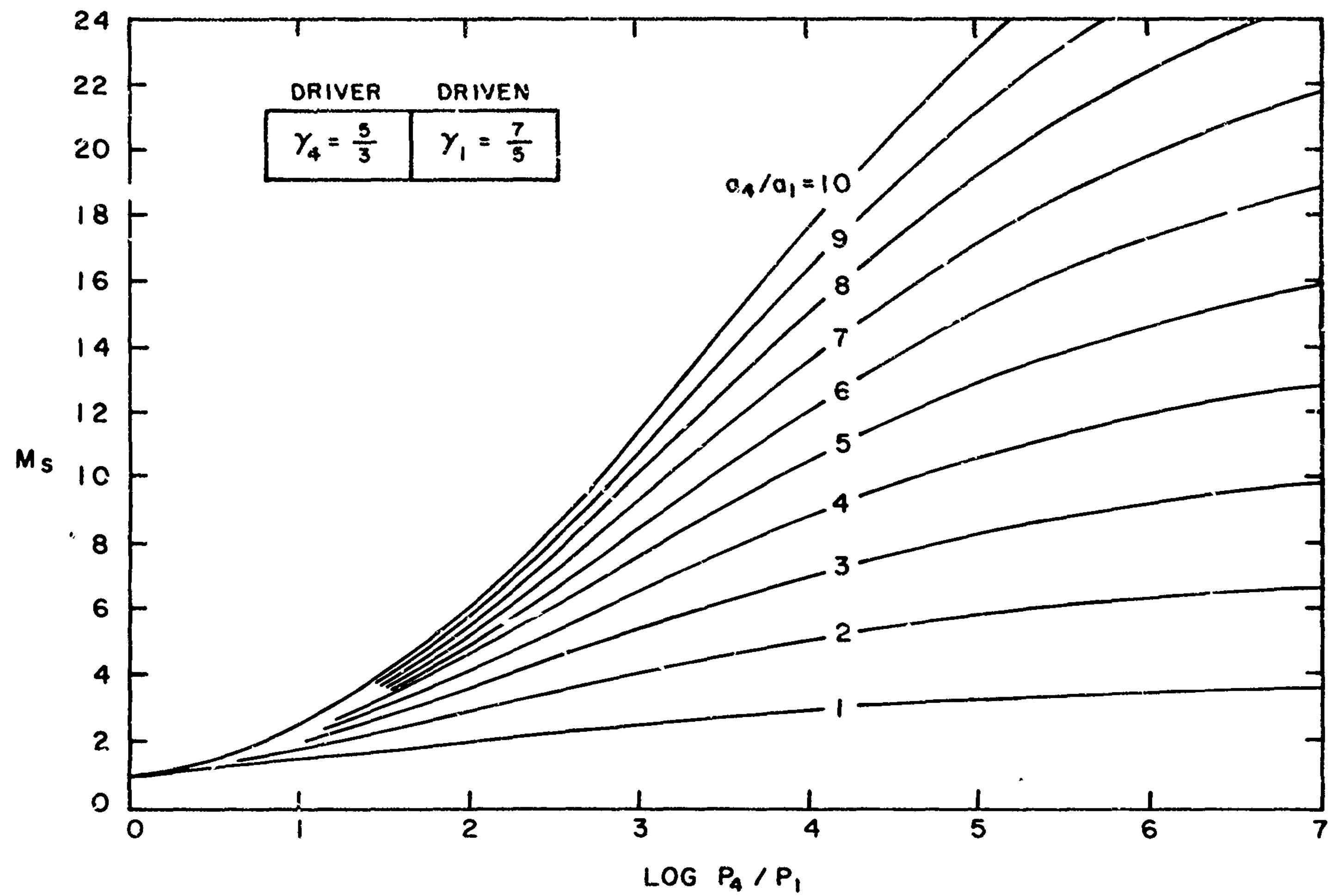

Figure 3. Shock-wave Mach number obtained from various pressure ratios for the case of a monatomic driven gas and a diatomic driven gas.

$$T_5/T_1 = \frac{a_5^2}{a_1^2} = [(\gamma_1 - 1)M_s]^{-2}[2(\gamma_1-1)M_s^2 + 3-\gamma_1][(3\gamma_1-1)M_s^2-2(\gamma_1 - 1)] \quad (17)$$

$$\rho_5/\rho_1=[2(\gamma_1-1)M_s^2-(\gamma_1-3)]^{-1}[(\gamma_1-1)M_s^2+ 2]^{-1}[(\gamma_1+1)M_s^2][2\gamma_1 M_s^2-(\gamma_1-1)] \quad (18)$$

The previously calculated maximum Mach numbers attainable in air for different drivers may be substituted in the above equations to obtain the results shown in table I.

Table I. Ideal Conditions Behind Primary and Reflected Shock Waves in Air

Driver gas	M_s	$\frac{P_2}{P_1}$	$\frac{P_5}{P_1}$	$\frac{\rho_2}{\rho_1}$	$\frac{\rho_5}{\rho_1}$	$\frac{T_2}{T_1}$	$\frac{T_5}{T_1}$
Air	6.	41.8	291.8	5.27	17.4	7.94	16.8
He	10.	116.5	885.4	5.71	19.6	20.4	45.2
H_2	24.	671.8	5326.1	5.95	20.7	112.9	256.8

The high temperature behind the reflected shock together with the condition that there is no flow in this region makes it attractive for performing chemical kinetic experiments. However, we shall see that the temperatures are lower and that other modifications occur as a result of actual gas behavior.

To be useful in the measurement of gas properties, the column of hot gas behind the incident shock wave must not be affected by the reflected expansion fan, and must be sufficiently long to provide for an adequate testing time. Figure 2 indicates that the length of the driver section and the distance from the diaphragm to the test station must be adjusted to achieve these goals. In addition, if a tube of the type shown in figure 2 is used, the distance between the test station and the end of the tube must be great enough that the reflected shock wave will not immediately pass over the gas processed by the incident shock wave. Reference 10 considers these points in some detail, while reference 6 gives for rarefaction limited case the expressions necessary to generate a diagram similar to figure 2 for a particular experiment. The work in both references is based upon the ideal case.

4. TECHNIQUES USED TO MODIFY SHOCK TUBE PERFORMANCE

The desire to increase the Mach number of the incident shock wave as well as the need to adapt the shock tube to particular ends has led to many modifications of the basic device: for example, extension of driving techniques to increase the strength of the shock and incorporation of various expansion sections in the gas flow behind the shock wave. Shock (wave) strength, sometimes denoted by the pressure ratio across the shock, will be denoted here by the Mach number of the shock.

4.1 Methods of Increasing Shock Wave Mach Number

Stronger shock waves may be obtained by increasing the area of the driver section relative to the area of the driven section. This effectively increases the pressure ratio across the diaphragm. For example, the effective value of P_4/P_1 is doubled if the diameter of the driver section is three times that of the driven section (ref 22). It may be noted that Seigal, who investigated the effect of repulsive and attractive forces between molecules of the driver gas (ref 24), concluded that the non-ideality thus introduced generally decreases the driving efficiency of constant-area shock tubes and increases the efficiency of nonuniform-area shock tubes.

Equation 13 has revealed the desirability of increasing the sound speed of the driver gas. This has been done in some shock tubes by heating the driver gas with an electrical heating element introduced into the driver section. This technique is limited to approximately 800°C by the pressure-temperature characteristics of materials. At this temperature, the sound speed of the driver gas is increased by a factor of 1.6 with an almost equal increase in the shock Mach number (fig. 3). One disadvantage of this type of heating is the effect it has on diaphragm performance.

Flash heating techniques avoid the adverse temperature effects of furnance heating. One type involves dumping large amounts of electrical energy into the driver gas by means of exploding wires. By use of this tecnnique, the temperature and pressure of helium drivers may be increased from room temperature and 200 psi to 20,000°K and 10,000 psi, and shocks with a velocity of 1.3 cm/μsec have been produced (ref 12 and 25).

In a second method of flash heating, inherent in electromagnetically driven shock tubes, energy is suddenly dumped into the gas by means of an electric discharge (ref 20).

Combustion or chemical heating is often used to heat the driver gas. Stoichiometric mixtures of hydrogen and oxygen have been burned in a heilium atmosphere to increase the temperature of the helium (ref 26). Combustion drivers with an overabundance of hydrogen, forming heated hydrogen drivers, and drivers composed solely of combustion products have also been used. Precautions are taken to avoid detonation of the combustion mixture since detonation is a safety hazard and also because pieces of the diaphragm are often torn off, becoming missiles that can damage the equipment. The large pressures and high temperatures achieved by combustion are partially offset by the increase in the mean molecular weight of the driver gas. The sound speed of the driver gas must be adjusted accordingly when calculations are made.

It is possible to heat the driver gas by subjecting it to an initial shock or strong pressure wave. This is done in what is usually referred to as a buffered or double diaphragm shock tube. The driven section of one tube is the driver for another section placed immediately downstream. It is possible to increase the shock velocity by about 20 percent by this means (ref 22). Pistons have also been used to heat the driver gas (ref 21) but these require a structurally stronger shock tube.

Calculations describing the simultaneous use of several of these techniques are given in reference 22.

4.2 Controlling Flow of Test Gas

4.2.1 Shock Tunnels

Techniques that convert the thermal energy of the shocked gas to kinetic energy by expanding the flow are generally used when simulating flight conditions at very high Mach numbers and altitudes and using models of flight vehicles within the tubes. A diverging nozzle section added to the end of the tube comprises what is known as a shock tunnel. The nozzle is often separated from the shock tube by a diaphragm and evacuated to increase the available testing time. A further increase in testing time in the shock tunnel may be gained by attaching a converging-diverging nozzle at the end of the shock tube. This reflects the shock wave at the nozzle entrance and the gas processed by the reflected wave acts as a reservoir for the flow through the nozzle. Reference 27 gives a summary of the work done on developing the shock tunnel.

Another modification of the shock tube, for the same purpose as the shock tunnel, is the expansion tube. In this device, the steady flow, varying area nozzle used in the shock tunnel is replaced by a non-steady flow, constant area expansion. Claims of higher performance characteristics than those of the shock tunnel have been made for this device (ref 1).

4.2.2 Tailored Interface Tubes

Reflected shock waves, while travelling toward the driver section, encounter the contact surface (fig. 2). The resulting wave interaction causes disturbances that propagate into the reflected shock-processed gas. These waves, which may be compressive or expansive, are controlled by the gases used, by the location of the expansion fan, and other geometrical considerations. Any such disturbance can be made extremely weak by matching acoustic impedances at the contact surface. This is commonly called the tailored interface technique (ref 22 and 28).

4.2.3 Single Pulse Tubes

The chemical, or single pulse, shock tube is used to elevate a test gas to a high temperature and then rapidly cool it, "freezing" in gas in its high temperature composition. Routine analytic means, such as gas chromatography are then used to investigate gas composition (refs 29, 30, 31). This heating-cooling effect is accomplished by subjecting the gas behind a reflected shock to an expansion wave generated by breaking a second diaphragm upstream of the reflected shock (ref 29) or by modifying the reflected shock-contact surface interaction (ref 30).

4.2.4 Dump Tank

If a test station is located near the end of the shock tube, the time available for studying gas properties behind the incident shock wave may be restricted by the time of arrival of the reflected shock wave. In this situation, the available testing time can be increased by installing a large volume tank at the end of the driven section of the tube. This dump tank may be separated from the shock tube by a diaphragm and evacuated. Since the pressure behind the reflected shock is much greater than the pressure behind the incident shock (table I), the dump chamber also serves to decrease the pressure in the system after the experiment thereby protecting windows and other equipment installed in the shock tube.

5. ACTUAL SHOCK TUBE BEHAVIOR

5.1 Gas Effects

The theory presented presumes that the gas constituents are constant throughout their flow history and that particle interactions do not play a role. The temperatures and densities over which the shock tube operates out-ranges these assumptions and one of the chief uses of the shock tube is the study of these real gas properties. Since these properties are described elsewhere in this volume, they will not be treated in detail here.

The existence of chemical reactions, including dissociation and ionization, together with particle interaction radically change the equilibrium thermodynamic properties predicted by equations 6 through 8 and 16 through 18. As an example, the density ratio ρ_2/ρ_1 in the ideal case cannot exceed 6.0 for a diatomic gas, whereas in a real gas this ratio is considerably higher.

The finite time that the internal degrees of freedom of the species behind the shock wave need to attain equilibrium, together with the time necessary for the chemical reactions to take place, results in a "relaxation zone" behind the shock front. The properties of gases in this nonequilibrium region have been widely studied in shock tubes (ref 32).

If the basic data are available, modern computing techniques make possible the calculation of the actual equilibrium (ref 5, 33) and nonequilibrium (ref 34,34) thermodynamic properties behind a shock wave. This information may be used in an experiment to check the validity of the data put into the calculation, to check the performance of a particular shock tube, or it may be used in the determination of gas properties.

The state of a shocked gas in a shock tube is not completely described by the theory so far presented even when real gas properties are known. Such phenomena as diaphragm rupture and boundary layer effects cause discrepancies that must be considered if accurate shock tube experiments are to be performed. The following is presented to point out how the real performance of the shock tube itself causes major variations from ideal theory.

5.2 Diaphragm Effects

Experiments have shown that the shock wave accelerates immediately after the diaphragm breaks (ref 36). This is usually attributed to the fact that the diaphragm does not rupture instantaneously. Studies have shown (ref 37,38) that most often the break in the diaphragm starts at the center and spreads to the edges. The gas flow therefore starts as a jet and increases as the diaphragm opens, until the cross section of the tube is filled, the shock wave being formed in this process. Distances ranging from 5 to 40 tube diameters have been referred to as being necessary for complete shock wave formation, although some data indicate the necessity for even greater lengths (ref 36).

The maximum velocity of a shock wave so produced sometimes exceeds the velocity predicted from equation 12. Theoretical investigations by White (ref 36) and Kireyev (ref 39) attribute

this to the effect of diaphragm opening characteristics. Shock tube flow is also affected if a piece of the diaphragm rebounds after it opens or if a fragment is torn off and propelled down the tube.

The diaphragm, therefore, is an extremely important factor in shock tube operations. Some work of a general nature has been done on diaphragm design (ref 39), but the choice for a particular job is still largely empirical. An aluminum diaphragm used in the Harry Diamond Laboratories 2-in. cross-section shock tube is shown in figure 4. This is cut from 0.062-in. 5054 aluminum sheet and scored to assure opening in a four-petal manner. It may be scored either by milling with an engraving tool or by stamping. The depth of the score is critical; too shallow a groove results in rupture pressures so high that a petal is likely to fragment; too deep a groove results in a rupture at a pressure too low to open the leaves completely. The optimum depth for the diaphragm shown is approximately 1/6 of the thickness.

The burst pressure is substantially affected by a number of other factors, such as variations in the diaphragm material, method of clamping or holding the diaphragm, and the method of applying the driver pressure. However, with care one can obtain reproducible burst pressures. The diaphragm shown in figure 4 can be used to obtain a burst pressure of 1500 psi. Accumulated data on diaphragm rupture are given in references 10 and 40.

5.3 Boundary Layer Effects

The shock wave reaches a maximum velocity and then begins to decelerate. Additional variations in shock speed further down the tube are possible (ref 12,41,42). These result in nonuniform gas properties, since gas entering a weaker shock is compressed and heated to a lesser degree. For this reason, the velocity history of a shock wave in the tube should be known and usually only data obtained from experiments involving a nearly uniform shock velocity are reported. Thermodynamic properties existing at points behind an attenuating shock wave may be estimated by the use of techniques given in references 43, 44, 45.

A major cause of shock wave attenuation is the loss of energy from the test gas to the boundary layer. A review of the boundary layer theories dealing with attenuation is given in reference 46. Other factors contributing to nonuniform shock wave velocities are nonuniform conditions existing in the driver section (ref 47), relaxation effects in the test gas (ref 48), and the energy lost by radiation (ref 49, 50).

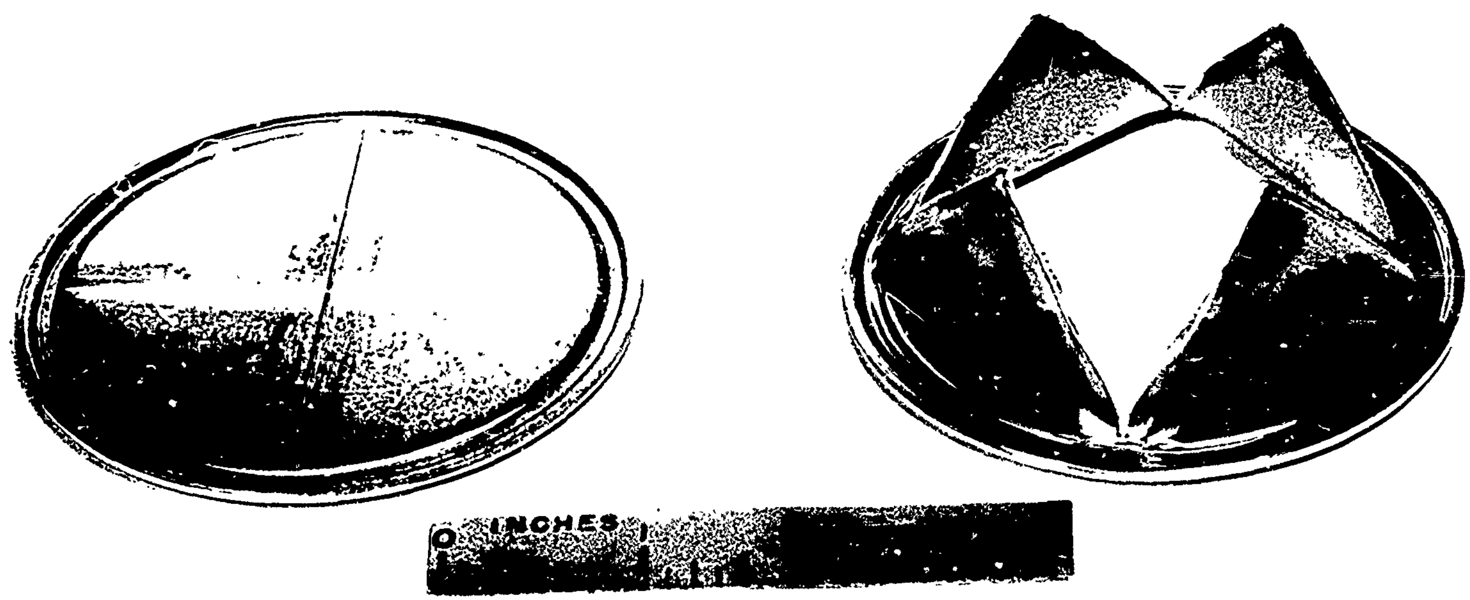

Figure 4. Shock-tube diaphragm before and after rupture.

Distinct curvatures of the shock front have been observed (ref 51 and 52). The curvature is primarily a function of the radius of the shock tube and the initial gas pressure. It should be taken into consideration in measurements of shock front thickness. Shock front curvature is analyzed on the basis of boundary layer effects in references 53 and 54.

The column of gas behind the shock wave is neither as long nor as homogeneous as predicted by ideal theory. The greater compressions taking place in real gases decrease the column length, and relaxation effects divide the gas behind the shock front into nonequilibrium and equilibrium regions. The boundary layer, in addition to introducing inhomogeneities along the wall, also decreases the column length, since it extends through the contact surface and passes test gas into the contact region (ref 55). The boundary layer may completely close the tube and /or may generate eddies at the contact surface, thus causing the contact surface to be a more diffuse region. Density variations in the driver section (ref 12) and mixing caused by the finite diaphragm opening time also contribute to a diffuse contact region. The associated loss in test time is particularly pronounced at low initial pressures (< 1 mm Hg), as reported in references 55 through 59. This accounts for discontinuity in the shock tube operating regime curves of figure 1, the data for low pressures referring to tubes of large diameter.

The boundary layer also plays an important role in reflected shock regions. After the shock wave reflects from the end wall it encounters the boundary layer caused by the flow behind the incident shock wave. After this encounter, the velocity of the reflected shock has been observed to vary from its calculated value (ref 60). The actual reflected shock velocity can be as much as 25 percent less than the calculated value (ref 61) in the case of a monatomic gas, and even greater in the case of a polyatomic gas. Experiments in polyatomic gases show that at the boundary layer the reflected shock wave divides into two or more shocks which generally move with nonuniform velocities. A theoretical analysis of the interaction of the shock wave with the boundary layer is given in reference 62.

Among the other factors contributing to the nonideal state behind a reflected shock wave are the relaxation zone behind the incident shock which is overrun by the reflected shock (ref 63) and the propagation of disturbances in the gas originally behind the incident shock through the reflected shock wave (ref 64). In addition, heat transfer takes place between the hot gas and the end wall (ref 65).

The temperature, density, and pressure immediately behind the reflected shock wave have been found to vary slightly from the calculated values. As the length of gas column behind the reflected shock increases, in many cases there is a small but steady change in the values of the gas thermodynamic variables. Much of the experimental work on gas properties behind reflected shock waves is summarized in reference 66.

5.4 Radiation Effects

The radiation emitted by the gas behind a shock wave can be absorbed by the cold test gas in front of the wave, thus raising the energy level of this test gas. The resulting change in the initial conditions of the test gas has been mentioned as the reason for discrepancies between measured and calculated gas properties in electromagnetic shock tubes (ref 67) as well as an explanation of the low xenon activation energies measured in a conventional shock tube (ref 68). Free (precursor) electrons detected preceding the shock wave have been attributed to photoionization of the cold test gas (ref 69), diffusion of electrons through the shock front (ref 70), and electron detachment from the shock tube wall by precursor thermal radiation (ref 71).

6. SHOCK TUBE INSTRUMENTATION

The instruments used in a shock tube experiment are usually located at fixed positions in the side wall of the tube, measurements being made as the shock wave and compressed gas pass these positions. Occasionally measurements are made at stations at the end of the shock tube. The high speed and short time duration of the flow require that the measuring system (consisting of sensors, signal modifiers, and recorders) have a high frequency response and good spatial resolution. Probes placed in the shock-tube wall are used to measure phenomena in the immediate vicinity of the probe, while devices that radiate across the entire gas column are used to obtain average values over the path length.

Boundary layers and other nonuniformities affect all types of measurements. The technique of placing sensors in aerodynamically shaped bodies that extend into the flow has been used in shock tubes to minimize boundary layer effects (ref 72). Similarly, stagnation measurements have been made in shock tubes by bringing the flow to rest in the vicinity of sensors placed at the nose of a blunt body (ref 73, 74).

The rest of this report will be devoted to the discussion of various measurements made in shock tubes. The references cited are meant to be representative of shock tube instrumentation and measurement techniques. Additional information will be found in references 6 to 18 and 75.

7. MEASUREMENTS

7.1 Pressure

The ability of pressure to change the electrical characteristics of a circuit has been widely exploited in the construction of electro-mechanical transducers. Devices are described in references 76 and 77 in which pressure acts upon a diaphragm and causes a change in the resistance of an attached grid of wire or a change in the capacitance between two conducting plates or generates a charge in a piezoelectric crystal.

Piezoelectric transducers, whose natural frequency is limited by the crystal unit to about 500,000 cps have gained wide acceptance in shock tube pressure measurements. Despite this relatively high frequency, the response of such a transducer is not sufficient to record many of the high speed fluctuations occurring in shock tube flows. In addition, the transducer diaphragm and associated electronics are generally driven to resonance (ringing) by the shock wave, making the interpretation of the output signal difficult. Special isolation mounting of piezoelectric transducers is required due to their sensitivity to the mechanical shocks and vibrations that precede the shock wave down the tube.

Metal bars may be used to transmit the pressure pulse from the shocked gas to the sensitive element. Piezoelectric crystals (ref 78) and strain gages (ref 79) have been used as the sensitive element. The use of a bar rather than a diaphragm eliminates a major source of ringing. The time available for testing when using a bar is limited by the reflection of the pressure pulse within the pressure-sensitive system. Bogonoff (ref 80) points out inherent limitations in the pressure rise-time properties of a bar and presents a transducer design having a rise time of 0.1 μsec.

Pressure transducers have been used to measured the pressure behind shock waves (ref 81) and to determine the duration of various flow regimes. In addition, the shock tube is often used as an instrument for the calibration of pressure transducers (ref 82).

7.2 Density and Concentration

Density and variation of density may be determined using techniques sensitive to the gross density of the gas or to one or more of the constituent gases. Optical measurements are particularly useful since they do not disturb the gas flow, are capable of fine spatial resolution, and are relatively easy to interpret. Schilieren and shadowgraph techniques which are sensitive to variations in the index of refraction of a gas which is dependent upon the density,

have often been used in qualitative work. Since the schlieren technique is sensitive to density gradient and the shadowgraph technique is sensitive to second spatial derivatives of the gas density, these techniques are particularly applicable to shock front photography. Details on the construction and use of schlieren and shadowgraph systems may be found in references 83 and 84.

Schlieren systems have also been used for quantitative work (ref 85 through 88). In one method (ref 85, 86) the length of a relaxation zone behind the shock wave has been measured by using a parallel light source whose length normal to the shock is greater than the relaxation distance. Changes in total intensity are measured with a phototube as a function of time. Measurements of this intensity variation give the region for which the density is changing, this region being correlated with the relaxation zone.

The interferometer, long a standard tool in optical measurements, has been applied to shock tube studies to measure gas density. The Mach-Zehnder modification of the Jamin interferometer has been widely used along with other types such as the Michelson (ref 89) and the Rayleigh double-slit (ref 90) interferometers to measure gas density. Although relatively expensive to construct and sometimes difficult to adjust for operation, the Mach-Zehnder interferometer has the advantages that its fringes can be focused on a plane inside the test section and the results are relatively easy to interpret.

The density change across the shock wave as measured by an interferometer is given by the expression

$$\Delta\rho = \frac{S\lambda}{K\ell}$$

where ℓ is the path through the gas, λ the wavelength of the light, S the change in the number of fringes, and K is the Gladstone-Dale constant

$$K = (n_o - 1)/\rho_o,$$

where n_o and ρ_o are the index of refraction and gas density at a reference condition.

The density is discontinuous across the shock front insofar as the interferometer resolving power is concerned and determining the fringe shift through a shock wave may become difficult. However, tracking may be done by using optics to offset the fringes on a recording film (ref 91) or by using a central fringe composed of many wavelength (white light). A difficulty is encountered

when using the central fringe since dispersion causes it to shift its location with respect to the other fringes (ref 92). Static calibration of the interferometer should be made if white light is used and the expected density change is relatively large.

An important problem with these refractive optical methods is that the shocked gas is often heated to the point where its light emission is comparable with that of the light source. The high intensity of a laser is useful when studying very bright subjects, particularly since the discreteness of the laser wavelength permits the use of filters to limit the amount of extraneous light seen by the recording film. The use of a laser as an interferometer light source is described in reference 93 and 94. A direct way of using lasers to measure gas density (ref 95, 96) is to pass the light from the laser through the test gas and then reflect it back into the laser. The output of the laser is amplitude modulated by the resulting interaction. The laser is thereby used as its own source and detector.

The Mach-Zehnder interferometer has been used in shock tubes to study relaxation phenomena (ref 97), chemical kinetics (ref 98, 99), boundary layers (ref 100), and the flow of shocked gases over bodies (ref 101). The Mach-Zehnder interferometer has also been used to study electron concentration in a shocked gas when conditions are such that the index of refraction is dominated by the contribution of free electrons (ref 92). This contribution, which is strongly dependent on wavelength, may be separated from the contributions of other species by obtaining simultaneous measurements at two different wavelengths. Extensive reviews of Mach-Zehnder operation, particularly from the point of view of measuring electron concentration, are given in references 102 and 103.

The absorption of X-rays and electron beams may be used to measure the density of a gas. To do this, it is assumed that the intensity, I, of a beam passing through an absorbing gas is controlled by the exponential law

$$I = I_o \exp(-u\rho\ell)$$

where I_o, u, ρ, and ℓ are the initial beam intensity, mass absorption coefficient, gas density, and path length, respectively. Although for X-rays the absorption coefficient is essentially independent of temperature, it is strongly dependent on wavelength. A stable X-ray source is therefore required (ref 75, 104). The sensitivity increases with increasing molecular weight because of the accompanying increase in the absorption. Shock tube experiments using X-ray absorption techniques (ref 105, 106) are effective at gas densities too low for interferometric techniques.

The use of an electron or other particle beam for absorption measurements is complicated by the need for small (10 to 20 μ) holes in the shock tube walls. Coverings which will pass the beam but withstand the shock have been used. Electron beams generated by heated sources are used in the experiments described in references 55 and 107, whereas β rays are used in reference 108.

Many species absorb radiation in the ultraviolet, visible, or infrared. A notable example is the ability of the molecular components of air to absorb ultraviolet radiation. This fact is widely used in density measurements, particularly in the determination of chemical rate constants. The absorption coefficient at these wavelengths may be temperature dependent, and this may cause some uncertainty in the measurement. Optical absorption experiments are described in reference 8, 109 and 110.

The characteristic spectra emitted by high temperature gases have long been used to identify gas constituents. Emission techniques are less widely used in quantitative shock tube density measurements than absorption techniques because of a lack of data on basic emissive properties. Nevertheless, emission techniques have been used to study various chemical kinetic (ref 111, 112, 113) and emission processes (ref 114).

Scattering processes have usually been applied to high speed gas studies when the gas is not sufficiently dense for interferometric or absorption techniques. The scattering beams can be made quite narrow for measurements across a path. Electron scattering measurements have been used in determinations of shock wave structure (ref 115) and oxygen relaxation rates (ref 116). Although, in general, electron scattering has been used, the intensity available from laser sources has led to interest in molecular and atomic scattering of electromagnetic radiation (ref 117, 118).

Certain metals immersed in an atomic gas act as a catalyst for atomic recombination. The change in the electric resistance of the metal caused by the heat liberated in the recombination process can be correlated with the atom concentration. This principle has been utilized in the "catalytic probe," which may take the form of a thin metallic film coated on nonconducting substrata (ref 119) or thin wires suspended in the gas (ref 120, 121).

As previously indicated, the chemical shock tube can be used to obtain complete information on the composition of a gas. Another technique for determining the composition of a shocked gas is to allow the hot gas behind a reflected shock wave to pass through a small hole in the end wall of the tube and into a time-of-flight mass spectrometer (ref 61, 122, 123).

The change in the intensity of light reflected from a shock front is proportional to the change in the density of the gas. The density of the gas, in turn, is dependent upon the excitation of its internal degrees of freedom. The rotational degrees of freedom are highly excited in most shock fronts. Extensive reflected light studies of shock front thickness and rotational relaxation have been carried out (ref 124).

7.3 Flow Velocity

The flow velocity of a sufficiently luminous gas may be readily measured by the use of time resolved photography. The luminosity may be enhanced by adding compounds that are easily excited (ref 81). If a fast acting shutter is used, the resulting "still" picture will yield qualitative information on the flow field.

The flow velocity may also be measured by placing a cone or a wedge in the flow and observing the resulting shock angle or detachment distance. The calculation of the velocity, however, requires knowledge of the actual gas properties (ref 125).

If an obstruction such as a perforated plate is placed in the flow, the shock-processed gas initially behind the plate passes through the perforations. A relatively discontinuous contact surface, separating this gas from that initially ahead of the plate, is formed downstream from the plate and travels at the flow velocity (ref 126).

Striking a small spark in the flowing gas behind a shock wave ionizes a small quantity of the gas. Photographing the displacement and distortion of a succession of such sparks then reveals the flow velocity and flow field. Such a technique has been used in low Mach number flows (ref 127, 128). Rudinger (ref 128) points out that precautions must be taken to add enough energy to yield a discernible result but not so much as to considerably modify gas properties.

A single wave may be generated in a flowing gas by an electrical discharge. If it is a weak wave, it will propagate with sonic speed plus or minus the uniform gas motion. A measurement of the upstream and downstream wave velocities will yield the flow velocity and the speed of sound. The temperature of the gas can be calculated if the gas constant and ratio of specific heats are known (ref 126).

Finally, small material particles, such as lycopodium powder, oil drops, and cigarette smoke, have been added as tracers in studies of boundary layer flows (ref 129).

7.4 Wall Temperature and Heat Transfer

The energy transferred to the wall of a shock tube or to a body immersed in the flowing gas may be measured by making use of a film of metal attached to an insulating back. The film is so thin that it will respond rapidly to temperature changes in the flowing gas. The film thickness used is governed by the diffusion depth

$$\lambda = \sqrt{k\tau}$$

where k is the thermal diffusivity of the metal and τ is the time needed for the temperature at a depth λ to rise to 1/e of the surface temperature. When the metal thickness is much less than the diffusion depth, temperature gradients across the film may be neglected and the instantaneous temperature of the insulating backing is sensed. The electrical resistance of the film therefore follows temperature changes closely and it may be used as a resistance thermometer. When the thickness of the metal is appreciably greater (e.g., equal to the diffusion depth), most of the heat passing through the surface of the film is trapped in the metal and the film may be used as a surface calorimeter to study the characteristics of heat flow from the hot gas into the film material. The thickness of thin-film gages is such that their response times range from 10^{-6} to 10^{-3} sec. Analyses of these gages, their construction and calibration techniques, together with limitations imposed by changes in the properties of the metal film and the gage interaction with ionized gases, are given in references 130 through 132.

In addition to the pure metal films described in the above references, elements made of nickel oxide (ref 133) and pyroelectric material (ref 134) have been considered. Thermocouples made of very thin elements have also been developed (ref 135).

One variation of the thin-film technique to measure wall temperatures lies in coating the film on a substrate, such as sapphire, that will pass infrared radiation. The film is heated by the hot gas and its radiation is viewed through the sapphire by a suitable infrared detector. While this eliminates certain difficulties encountered in ionized gas flow, it is more complicated and less sensitive than measuring the change in the electric resistance of the film. Construction and applications of the infrared gage are discussed in references 136 and 137.

Thin film temperature gages have been used in studying boundary layer phenomena (ref 138) and also convective (ref 139) and radiative (ref 140) heat transfer rates.

7.5 Gas Temperature

A very important quantity that is difficult to measure is the temperature of the shocked gas. The large and rapid changes in temperature behind the shock wave preclude the use of such mechanical devices as thermocouples. Boundary layer effects do not permit the extrapolation of the wall temperature to the gas temperature away from the wall. In addition, the definition of temperature becomes complicated in a relaxation zone (ref 141). References 142 through 146 contain reviews of high temperature optical measurements made in gases and plasmas.

Many temperature dependent aspects of optical spectra have been used to determine gas temperatures in shock tubes. A widely used technique involves viewing a continuous light source through a hot gas containing a metal vapor. The resonance lines from the spectrum of the metal are visible as dark absorption lines if the gas is cooler than the light source. The lines are brighter than the source if the gas is hotter. If the gas and light source are at the same temperature, the lines disappear. As described above, this spectrum line reversal technique yields quantitative information only at the reversal point, i.e., when the gas and source are at the same temperature (ref 9). Methods of obtaining quantitative information using this technique over a range of temperatures are given in references 147 and 148. The upper limit for this technique, currently under $6000^{\circ}K$, is imposed by the temperature of the light source.

Uses of molecular spectra, which are easily excited in conventional shock tube operations, include measurements of the rotational line intensity of CN (ref 149, 150), of the relative intensities of two wavelength regions in a vibration-rotation band of OH (ref 151), and of the variation of the molecular band structure emitted by nitrogen in the nonequilibrium zone (ref 152). The use of absolute and /or relative line intensities and of continuum radiation has been restricted largely to electromagnetic shock tube operations, although the intensity of chromium lines (ref 81, 153) and argon continuum radiation (ref 154) have been used in conventional tubes. Brightness temperatures have been determined using the emitted radiation and emissivity (ref 155, 156).

Interactions involving radiating particles may cause a change in a spectral line. For example, in the Stark broadening of a spectral line, there is the interaction between a radiating particle and the local electric field. Thermal, or doppler-like broadening, may also be significant. Tables of quantitative data (ref 144) are available for interactions of both electrons and ions. The degree of broadening of any line is dependent upon the the electron concentration and the gas temperature. Experiments utilizing line broadening are described in references 157 and 158.

The analytic expressions for the absorption coefficient of molecular oxygen, developed in reference 159, show that the ratio of the coefficients of any two wavelengths is a function of the gas temperature only. The technique is fully described in reference 160. In addition, as mentioned in the section on the measurement of flow velocity, sound waves may be used in the measurement of temperature.

7.6 Electrical Properties of an Ionized Gas

The propagation characteristics of electromagnetic wave in ionized gases have been widely studied in shock tubes. The linearlized wave equation formed from Maxwell's equations combined with the fluid dynamic equations is the basis for this work. In the absence of external magnetic fields the electromagnetic wave is assumed to interact with a free electron, and damping forces are provided by electron-molecule collisions. The solution of these equations may be expressed in terms of either the complex conductivity (ref 161) or the complex dielectric constant (ref 162). In this model, "cut off" occurs at the plasma frequency and therefore wave propagation requires frequencies greater than the plasma frequency.

The boundary conditions used in the solution of the electromagnetic wave equations depend upon the geometry of the experiment and the measurement technique. A widely used assumption is that the gas forms a semi-infinite homogeneous slab (ref 161). However, effects of electron density gradients have also been considered (ref 162 and 163). The shocked gas has been studied from the point of view of wave propagation in free space (ref 164) in a gas-filled waveguide (ref 165), or in a cavity (ref 166). A thorough discussion of electromagnetic wave-plasma interactions will be found in references 161 and 167.

The microwave frequency range (10^9 - 10^{11} cps) is widely used in electromagnetic wave propagation studies. This is due to the degree of interaction of microwaves with the gases generated in reentry phenomena and to their widespread use in communication and surveillance work.

The intensity change and phase shift of the transmitted microwaves are two of the quantities measured in shock tube work. Application of such changes have been made in studies of ionization phenomena in air (ref 168), noble gases (ref 169), and thermonuclear plasma generating machines (ref 170). The use of reflected intensity and phase measurements has the advantage that the range of the measurement is increased (ref 161). Reflected energy measurements are described in references 171 through 174. The

latter measurements are not restricted to side wall test stations but also include measurements made from a test station at the end of the shock tube.

The energy emitted at microwave frequencies has been correlated with the temperature of the emitting gas (ref 175), and preliminary shock tube measurements of this quantity have been made (ref 176).

The magnetic field at the center of a coil is perturbed by a change in the conductivity of the medium located inside the coil. A coil carrying direct current may be placed around a shock tube having nonconducting walls. The change in the conductivity of the moving gas causes a change in the magnetic field which, in turn, induces an EMF in a nearby search coil. Calibration is made by propelling material of known conductivity through the coils.

A variation of the magnetic coil technique measures the apparent impedance change caused when the conductivity of the medium in the center of the coil varies. This system has the advantage that it measures electrical conductivity directly, whereas the previous arrangement measures the spatial derivative of the conductivity. Various coils have been described (ref 177-178), and some have been used to study the conductivity of argon (ref 179) and of air (ref 180, 181).

Langmuir probes inserted in an ionized gas are used to measure the current drawn as a function of the applied probe voltage. These data can be used to determine electron and ion concentration and temperature (ref 182, 185).

Erratic results have previously been reported for probes located in the side walls of shock tubes since the effects of boundary layers (ref 179, 186 - 188), chemical contamination, (ref 189), and various interactions between the charged particles and the electric field of the probe (184, 190) have not been properly considered. Theoretical and experimental work using stagnation point Langmuir probes is given in references 74 and 191. Studies of boundary layer effects on probes are discussed in references 192 and 193.

Probe techniques have also been used in shock tubes to measure the Hall currents generated when an ionized gas flows through a magnetic field (ref 194). Another technique places a high frequency signal on a probe and determines the gas parameters from measurements of the "cut off" frequency or plasma impedance characteristics. Such techniques have been used in plasma generators (ref 195, 196).

7.7 Shock Velocity

Gas properties can readily be calculated in terms of the shock Mach number. This is particularly useful since shock velocity measurements are relatively easy to make in conventional shock tubes. Such measurements are most often made by noting the time of arrival of the shock at stations equally spaced along the tube. Any quantity that is changed from its original state by the shock wave and that can be readily measured may be used. Thus, thin film thermometers, pressure gauges and switches, light beams, light emission and ionization gauges have been used (ref 10) to measure shock velocity. The interaction of the high temperature gas with a beam of positive ions (ref 197) and glow discharge gauges (198) which use the breakdown of the gas between two charged probes, have also been used. The sensitivity of the last three techniques is considered in reference 199.

The signals thus generated may be used to activate electronic timers or may be displayed on oscilloscope screens, when the electron beam is usually swept back and forth across the tube face, making possible high temporal resolutions.

A continuous measure of the shock velocity can be made photographically if the gas behind the shock is made luminous. Continuous measurements can also be obtained by measuring the doppler shift of microwaves reflected from the ionized front behind a shock wave, although some anomalous results using this technique have been noted (ref 200, 201).

The review given in the preceding pages outlines the techniques and instrumentation currently in use in conventional shock tubes. It can be seen that, while complicated, the shock tube provides a suitable tool for investigations into the extreme thermodynamic conditions encountered in modern technology.

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13. ABSTRACT

A survey of shock tube techniques and instrumentation is presented. Ideal shock tube theory is outlined as are various phenomena which influence actual performance. Shock tubes designed for specific purposes are described. Shock tube instrumentation is discussed in terms of the variable to be measured.

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